A Statistical study of giant flux ropes in the magnetized ionosphere at Venus

T. L. Zhang¹,², W. L. Teh², W. Baumjohann², R. Nakamura², E. Dubinin³, Y. Wei³, C. T. Russell⁴, J. G. Luhmann⁵, K. H. Glassmeier⁶, H. Y. Wei⁷, A. M. Du⁷, Q. M. Lu¹, S. Wang¹, M. Balikhin⁸

¹CAS Key Laboratory of Geospace Environment, University of Science and Technology of China, Hefei, China
²Space Research Institute, Austrian Academy of Sciences, Graz, Austria
³Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, Germany
⁴IGPP, University of California, Los Angeles, USA
⁵Space Sciences Laboratory, University of California, Berkeley, CA, USA
⁶IGEP, Technischen Universität Braunschweig, Braunschweig, Germany
⁷Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China
⁸University of Sheffield, Sheffield, UK

Abstract

Examination of Venus Express magnetic field measurements during solar minimum has revealed the presence of giant flux ropes in the magnetized ionosphere. A total of 77 large flux rope events were identified between July 2008 and October 2009. These flux ropes all have strong core fields tending to be aligned with the planetary surface. They appear as isolated events during each spacecraft ionospheric passage. Using the superposed epoch method, we find the averaged core field is about 45 nT, which is well above the average ambient ionospheric field of 20 nT, with a full width at half maximum (FWHM) duration of 32 second, equivalent to a width of about 300 km. These giant flux ropes are found to be quasi-stationary. Considering the rope axial orientation preference and spacecraft trajectory geometry, we conclude that the giant flux ropes appear quite often with an occurrence
frequency of more than 33% during solar minimum. They do not show a preference for any particular Interplanetary Magnetic Field (IMF) orientation, but they apparently occur near the “magnetic polar” region rather than the “magnetic equator”. The flux ropes are found most frequently in the –E hemisphere, determined from the IMF orientation. The rope axis is mainly quasi perpendicular to solar wind flow direction and the core field orientation is highly correlated with IMF B_Y direction. It is suggested that the giant flux ropes are formed due to the solar wind interaction with Venus, most probably in the magnetotail, and later being transported and deposited in the ionosphere at the terminator.

**Introduction**

Magnetic flux ropes, one of the most ubiquitous features in space plasmas, are helical twisted magnetic field structures. They are present throughout the solar system, e.g., at the Sun, in the interplanetary space, in the Earth’s magnetosphere, and around other planets. The planetary flux ropes can be divided into two categories: magnetospheric or ionospheric flux ropes. The magnetospheric flux ropes include magnetopause flux transfer events (FTEs) at Earth and Mercury (Russell and Elphic, 1979a; Slavin et al., 2009a), and plasmoid ejections from the magnetotails of Earth, Jupiter, Saturn, Mercury, and Venus (Russell, 1974; Russell et al., 1998; Jackman et al., 2007; Slavin et al., 2010; Zhang et al., 2012a). The formation of the magnetospheric flux ropes is caused by magnetic field reconnection.

The ionospheric flux ropes, embedded in the planetary ionospheres, are observed at Venus, Mars, and Titan (Russell and Elphic, 1979b, Cloutier et al., 1999, Wei et al., 2010). The first observation of ionospheric flux ropes was made at Venus by the Pioneer Venus
Orbiter (PVO) mission (Russell and Elphic, 1979b) at solar maximum. These flux ropes at Venus were extensively studied in the main PVO mission phase during solar maximum, when the periapsis of the spacecraft was kept at 150 km altitude (cf. Russell, 1990). They are present as intense filamentary enhancements in magnetic fields formed from bundles of twisted magnetic field lines surrounded by ionospheric plasma. They are observed at all solar zenith angles on the dayside characterized by numerous events during one single ionospheric passage, with randomized axial orientation and a typical 10-km scale (Elphic and Russell, 1983).

Observations with PVO indicate that the occurrence of the flux ropes is strongly controlled by the ionosphere magnetic state which in general falls into two broad categories, unmagnetized and magnetized, depending on the pressure balance between the solar wind dynamic pressure and ionospheric thermal pressure (Luhmann et al., 1980). It is found that for normal solar wind dynamic pressure at solar maximum, about 70% of time, the Venusian ionosphere has sufficient thermal pressure to stand off the solar wind well above the atmosphere and is basically magnetic field-free. Although dayside ionosphere of Venus at solar maximum has a very low average field strength in general for such an unmagnetized ionosphere state, typically only ~ 1 nT, it is often populated with the flux ropes (Russell and Elphic, 1979b). But when the solar wind pressure becomes high, the ionosphere becomes magnetized and the flux rope formation process appears to be suppressed.

While PVO made in situ ionospheric observation during solar maximum, Venus Express has probed the Venus plasma environment during solar minimum since it orbital insertion on April 2006 (Titov et al, 2006; Svedhem et al., 2007). In the main mission phase of the first
500 days, the spacecraft periapsis was above 250 km altitude, just slightly higher than the
typical dayside ionopause altitude of 250 km during solar minimum (Zhang et al., 2007;
Zhang et al., 2008). Thus no in situ measurements the magnetized ionosphere were made
during this period except during few cases of extreme solar wind conditions when the solar
wind dynamic pressure is lower than ionospheric thermal pressure. Under this extreme solar
wind condition when the ionosphere behavior resembled the solar maximum situation, indeed
flux ropes were observed with characteristics similar to their counterparts found at solar
maximum by PVO in the unmagnetized ionosphere (Zhang et al., 2008, Wei et al., 2012).

Since the solar wind is usually stronger than the maximum ionospheric pressure at Mars,
we expect the Martian ionosphere to be magnetized under typical solar wind condition and
thus flux ropes seen less frequently. Indeed, early observations of the Mars Global Surveyor
(MGS) spacecraft indicate that flux ropes present only in 5% of the orbits in the Mars
ionosphere (Cloutier et al., 1999, Vignes et al., 2004). These Mars flux ropes have a width of
the order of a few tens of kilometers, and their axial orientation appears to be random in the
ionosphere. The Mars ropes are found to have global characteristics similar to those of Venus
as observed by PVO.

Recently, another type of flux rope has been observed both in the ionospheres of Mars
and Venus (Brain et al., 2010, Zhang et al., 2012b). It distinguishes itself from the PVO type
flux ropes by its large size of hundreds of kilometers and strong core field. Since the first
report of large scale flux ropes at Mars by Brain et al. (2010), several statistical studies have
been performed using the Mars Global Surveyor (MGS) data (Morgan et al., 2011, Beharrell
and Wild, 2012). It is found that these large scale flux ropes occur in the southern hemisphere
and near the strong crustal fields of Mars. The formation of the large flux ropes at Mars is attributed to the magnetic reconnection process between the interplanetary magnetic field and crustal field. This process occurs frequently and may aid in as much as 10% of the total present-day ion escape from Mars.

We have not observed evidence of crustal remnant magnetic field at Venus. The planet surface is at high temperature comparable with Curie temperature, so there should be no crustal fields capable of reconnecting with the interplanetary magnetic field to form flux ropes in the ionosphere. Thus the discovery of giant flux ropes in the Venustian ionosphere resembling to their counterpart at Mars is quite a surprise (Zhang et al., 2012b). Observations with Venus Express indicate that these giant flux ropes are quite different from the earlier PVO observation of smaller ionospheric flux ropes in many aspects. Firstly, these giant ropes occur in the magnetized ionosphere, while the PVO flux ropes are found in the unmagnetized ionosphere with nearly zero ambient fields. Secondly, the giant flux rope has a scale of several hundred km, similar to the vertical scale of the ionosphere (less than 200 km). The PVO flux ropes are tiny filamentary 10 km scale structures (e.g., Russell, 1990). Thirdly, the giant rope is an isolated single event for each periapsis passage of the spacecraft with orientation in the horizontal direction, while the PVO flux ropes are numerous for each orbital passage of ionosphere and their orientations are random (Russell and Elphic, 1979b).

Data and event selection

Since its orbital insertion on April 2006, Venus Express has surveyed Venus plasma environment through a complete solar minimum duration. Initially, its periapsis was at 78°
latitude and 250 km altitude during the main phase of the mission (Titov et al., 2006; Svedhem et al., 2007). Later, the spacecraft periapsis moved to higher latitude and lower altitude. On July 15, 2008, the periapsis was lowered to an altitude of 221 km from 357 km the previous day. Since then, Venus Express kept its periapsis altitude around 200 km for about two Venus years (1 Venus year = 224.7 days). On Oct 20, 2009, the periapsis moved back to an altitude of 243 km from 174 km the day before. Figure 1 shows Venus Express periapsis altitude variation during July 15, 2008 to October 19, 2009. Also shown are the monthly averaged sunspot numbers. It is clear that Venus Express probed the ionosphere during this period well below the ionopause/the photo-electron boundary which is about 250 km altitude (Zhang et al., 2007; Martinecz et al., 2009; Angsmann et al., 2011).

In this study, we examine magnetometer data during July 15, 2008 to October 19, 2009 taking the advantage of lowered spacecraft orbital periapsis. Figure 2 shows the spacecraft orbital trajectories during this period in VSO coordinates where the X axis points from Venus to the Sun, the Y axis is opposite to the Venus orbital motion and Z axis is northward. For easy illustration, only every 5th orbit is depicted. The straight lines are the orbital trajectory and the black dots are the periapsis locations for each orbit. It is clear that all periapsis passages are in a very limited region in the northern pole, within 86° to 94°, mostly with 88° to 92° solar zenith angle (SZA).

Figure 3 shows examples of the magnetic field strength observed near periapsis by the Venus Express magnetometer from 16 consecutive passes. The magnetic field data (Zhang et al., 2006) have 1-sec resolution and the time series are displayed as time around periapsis. As the examples in Figure 1 illustrate, one some of the orbits, the magnetic field has an
extraordinary enhancement near the periapsis, well above the background magnetized ionospheric magnetic field. The field enhancement occurs as an isolated single event, unlike the field enhancements in the unmagnetized ionosphere during solar maximum observed by PVO (Elphic and Russell, 1983). The giant flux ropes are found quite frequently. More than one hundred events were identified during July 2008 and October 2009. In this work, we imply a rather strict condition that the field enhancement must be at least twice the ambient field. We obtain 77 events for further statistical study. Figure 4 shows the occurrence of the giant flux ropes as functions of altitude and SZA.

Giant flux rope occurrence rate

Between July 15, 2008, and October 19, 2009, there are 428 days’ data available in this study, the missing data are largely due to the fact of Venus superior conjunction when the Venus is behind the Sun and spacecraft telemetry rate are largely reduced. Since the giant flux ropes occur as an isolated during any spacecraft periapsis passage, a simple way to estimate the occurrence rate is to divide the event number of 77 by the 428 days. Then we have an occurrence frequency of 18%. However, such a number could be much underestimated since the observation of flux ropes is highly directionally dependent. It is well known that the signatures of a flux rope are most prominent when the spacecraft travels through the center of the rope. When the spacecraft travels parallel to the rope axis, no signatures would be detected. Figure 5 shows the spatial distribution of the selected 77 giant magnetic flux events. Here we see that these events have a preference to occur at low altitudes as the spacecraft crosses the terminator plane, i.e., when the trajectory is aligned with the Sun-Venus line. Figure 6 shows
the event occurrence rate as a function of the angle between spacecraft trajectory and the Sun-Venus line. The events are sorted in 15° bins and event numbers in each bin are: 24, 20, 14, 12, 7, 0, respectively. From Figure 6 we see that 44 events, more than half of the total events, occur when the spacecraft trajectory within 30° of the Sun-Venus line.

That few or no giant flux ropes are observed when the spacecraft is flying along the dawn-dusk terminator line does not mean that the flux ropes are not there, it might suggest that the rope axis prefers to be perpendicular to the Sun-Venus line. To verify this, we determine the principal axis of the flux ropes using minimum variance analysis. It is found that giant flux ropes tend to be aligned approximately parallel to the planetary surface. In Figure 7 we depict the rope axial distribution in the XY plane of VSO coordinates. It is shown that the giant flux rope axes prefer to be in the direction perpendicular to the Sun-Venus line. Further in Figure 8 we show that 67 out of 77 events have rope axes more than 45° to the Sun-Venus line, i.e., quasi perpendicular to the direction from which the solar wind flows.

Considering the rope axial orientation preference and spacecraft trajectory geometry, we estimate the giant flux rope occurrence frequency using only the situation when the spacecraft is travelling nearly perpendicular to the rope axis. During 73 orbits in which the spacecraft is flying within 15° along the Sun-Venus line, 24 events are found. Thus we obtain a giant flux rope occurrence frequency of 33% at solar minimum.

Superposed epoch study

The data used in this study are the Venus Express magnetic field data. We identify the
giant flux rope events by the enhancement in the field strength and bipolar signature in the magnetic field components. Seventy-seven events were selected by imposing a strict condition that the enhancement in the field strength must be at least twice higher than the ambient field. Since the principal axis of the giant flux rope is mainly in the XY plane of VSO coordinates, the bipolar signature is mostly identified in the Bz component. Figure 9 displays the magnetic field profiles from all 77 selected events. The magnetic field component Bz and field magnitude are plotted as functions of minutes from the maximum magnetic field strength. The flux rope features are obvious and they are embedded in a magnetized background. By averaging these 77 magnetic profiles, we obtain a superposed sample of the giant flux rope. The averaged flux rope has an enhanced field strength peaked at 45.5 nT, well above the ambient field which is 20 nT. The duration of the flux rope profile is about 1 minute. Assuming the flux rope is stationary and taking the spacecraft orbital speed near periapsis at ~ 10 km/s, we obtain a flux rope scale size about 600 km, which is indeed giant, much larger than the size of flux ropes observed by PVO which is in the order of 10 km.

In order to validate our assumption that the giant flux ropes are stationary, we perform the following analysis. In Figure 10 we first display the averaged magnetic strength profile obtained from 77 events, we then take a trending line from the ambient magnetic field. After detrending the data, we are able to calculate the full width at half maximum (FWHM) duration of the flux rope. The averaged profile has a FWHM duration of 32 second and peak field of 45.5 nT. Further we divide our event data base into two parts according to the direction of motion of the spacecraft: 41 events are found as Venus Express moves from
nightside to dayside, and 36 events are found from dayside to nightside. Figure 11 shows the superposed epoch analysis for these two situations. After detrending, for both situations, the magnetic field profile of the flux ropes is essentially the same. When the spacecraft moves from nightside to dayside, the flux rope has a duration of 31 seconds and peak field of 44.6 nT. And when Venus Express moves from dayside to nightside, the flux rope has a duration of 34 seconds and peak field of 46.5 nT. The above finding that the flux rope duration does not depend on the spacecraft motion indicates that the spacecraft is travelling much faster than the magnetic structure. Thus the giant flux ropes are stationary at terminator.

**Interplanetary magnetic field (IMF) control**

In order to obtain the IMF values, we select the orbits when the interplanetary magnetic field is relative steady, defined by directional changes of the IMF between inbound and outbound of less than 30°. Out of 77 flux rope events, we were able to determine the IMF conditions on 52 events. Figure 12 shows the IMF vectors in VSO coordinates. To find out if giant flux ropes prefer any special IMF condition, we also display in the figure the IMF vectors, derived from 10 minute averaged magnetic field data in the solar wind at spacecraft apocenter, for all 428 days during solar minimum between July 2008 and October 2009. From Figure 12, we find that the giant flux ropes do not show a clear preference for a particular Interplanetary Magnetic Field (IMF) orientation.

In studying the solar wind interaction with Venus, it is common to convert data into the so-called IMF magnetic field coordinate since Venus has no intrinsic magnetic field and the configuration of the induced magnetosphere is affected by the IMF orientation. Figure 13
shows the flux rope event spatial distribution in such a magnetic coordinate where the X is antiparallel to the solar wind flow (the orbital motion of Venus is taken into account by considering the average aberration angle of 5°), the Y axis is aligned with the cross-flow component of the interplanetary magnetic field, and the Z axis is aligned with the motional electric field, i.e., in the $-V \times B$ direction. Several features can be identified from this figure. Firstly, the flux ropes prefer to occur in the “magnetic polar region” than at magnetic equator. Secondly, flux ropes prefer to occur in the $-E$ hemisphere. There are 34 events in the $-E$ hemisphere, in comparison to 18 events in the $+E$ hemisphere. In Figure 13, we display two bipolar signatures, the red dot denotes the bipolar signature from positive to negative and the black dot denotes the bipolar signature from negative to positive, if the spacecraft were travelling from nightside to dayside. It is apparent that the positive to negative bipolar signatures are mainly found in the $-Y$ side and negative to positive bipolar signatures prefer in the $+Y$ side.

**Rope core field orientation**

One of the major features used to identify the giant flux ropes is the strong core field enhancement. Since the rope axis is mainly quasi perpendicular to the solar wind, the core field is easily seen in magnetic $B_Y$ component in VSO coordinates. Figure 14 displays examples of core field enhancement in $B_Y$ component, also plotted is the total field strength in grey lines. The depicted intervals are selected to include the solar wind IMF conditions, bow shock inbound and outbound crossings, the core field enhancement peak. The core field exhibits as a sharp spike. An amazing property is that the core field always in positive
direction, i.e., a $+B_Y$ spike, no matter if the IMF $B_Y$ were positive or negative.

Figure 15 shows the core field orientation for all 77 events. It is evident that the core field is always in $+Y$ direction in VSO coordinates. In other words, when the IMF $B_Y$ in $+Y$ direction, the flux rope core field keeps the same direction as the IMF in $Y$ component; when the IMF $B_Y$ in $-Y$ direction, the flux rope somehow reverse its core field direction.

Figure 16 displays the giant flux core field spatial distribution in the YX plane of the IMF magnetic coordinate in which the $Y$ is aligned with IMF $B_Y$ in direction. The hemispheric asymmetry of the core field direction is evident, and it resembles the hemispheric asymmetry of the magnetic field wrapping pattern in the Venusian magnetotail observed by Zhang et al. (2010).

**Discussion and conclusions**

Since the nature of the flux ropes formation at Venus or at Mars is still subject for discussion, information on where and what circumstances they are found in the ionosphere is crucial to understanding how they arise and evolve. Examination of Venus Express magnetic field measurements during solar minimum has revealed the presence of giant flux ropes in the magnetized ionosphere. They occur quite frequently, with an occurrence rate of 33% between July 2008 and October 2009. We determine the average magnetic profile of the giant flux ropes and we find that these structures are essentially stationary at terminator.

The formation mechanism is apparently solar wind interaction related. The flux ropes prefer to orientate in the direction perpendicular to which the solar wind flows and they prefer to occur in the “magnetic polar” region than the “magnetic equator”. They are
observed more often in the –E hemisphere.

The finding of the hemispheric asymmetry of the giant flux core field direction sheds much light on understanding where and how the giant flux ropes form. Looking around Venus plasma environment, near magnetotail is the only other place where such a hemispheric asymmetry pattern exists (Zhang et al., 2010). In addition, large flux ropes have been observed in the Venus magnetotail (Slavin et al., 2009b, Zhang et al, 2012a). Thus the strong fields at terminator may be formed in the nightside and later transported and deposited in the ionosphere at terminator. Unfortunately, we are unable to probe the geometry of these structures as we always pass through them at the same place, at the north pole. Hence we do not know if these structures resemble plasmoids found by reconnection nor if they have the rope-like structure characteristic of plasmoids of the Earth. They also could be the magnetic manifestation of the plasma clouds seen on Pioneer Venus.

Acknowledgments.

The work in China was supported by NSFC grant (41174156, 41121003) and CAS Key Research Program KZZD-EW-01-4. The work at Graz was supported by Austrian Science Fund (FWF: I429-N16, P21051-N16). The work at UCLA was supported by the National Aeronautics and Space Administration under research Grant NNX10AV29G.
References


Zhang, T. L., et al. (2010), Hemispheric asymmetry of the magnetic field wrapping pattern in the Venusian magnetotail, Geophys. Res. Lett., 37, L14202,

Figure 1. Venus Express periapsis altitude variation with time during July 15, 2008 – October 19, 2009. The grey dots are the monthly averaged sunspot numbers.
Figure 2. Venus Express orbital trajectories during July 15, 2008 – October 19, 2009 in VSO coordinates. For easy illustration, only every 5th orbit are depicted. The straight lines are the orbital trajectory and the black dots are the periapsis for each orbit.
Figure 3. Examples of the magnetic field strength observed by the Venus Express magnetometer from 16 consecutive passes around ±3 minutes from each periapsis. Strong field enhancements are present in some of the passes. Events on May 14, 17, 18, 19, 20, 22, 23 are selected for statistics.
Figure 4. Giant flux rope events distribution as functions of altitude and solar zenith angle (SZA).
Figure 5. Spatial distribution of giant flux rope events in the XY plane in the VSO coordinates, which is about parallel to the surface of the Venus planet in the northern polar region. The black dots are the 77 giant flux rope events selected in this study and the grey lines are the corresponding orbital trajectories.
Figure 6. Occurrence rate as a function of the angle between spacecraft trajectory and the Sun-Venus line.
Figure 7. The spatial distribution of the giant flux rope axis in XY plane of the VSO coordinates.
Figure 8. Occurrence rate as a function of the angle between rope axis and the Sun-Venus line.
Figure 9. Superimposed giant flux rope magnetic field profiles of the 77 selected events. Note that the magnetic field Bz component of the flux ropes have been transformed into the same bipolar directions.
Figure 10. The averaged magnetic field profile of the giant flux ropes from all 77 selected events as functions of minutes from the maximum field enhancement. The dash line in the left figure is the trending line for the ambient magnetic field. In the right figure, the averaged magnetic field profile has been detrended, the FWHM duration is 32 second and the peak field is 45.5 nT.
Figure 11a. Superposed epoch study for the 41 events when the spacecraft travelling from nightside to dayside. Comments of Figure 10 caption apply. The FWHM duration is 31 s and the peak field is 44.6 nT.
Figure 11b. Superposed epoch study for the 36 events when the spacecraft travelling from dayside to nightside. Comments of Figure 10 caption apply. The FWHM duration is 34 second and the peak field is 46.5 nT.
Figure 12. IMF orientations. Black lines with arrows are the IMF orientations for the 52 giant flux rope events for which the IMF were determined. Grey lines are the IMF orientations for each day between July 2008 and October 2009.
Figure 13. Giant flux rope spatial distribution in the magnetic coordinates. The red dots denote a bipolar signature from positive to negative while the black dots denote a bipolar signature from negative to positive, if the spacecraft were travelling from nightside to dayside.
Figure 15a. Examples of giant flux ropes when the IMF $B_Y$ component is positive or nearly zero.
Figure 15b. Examples of giant flux ropes when the IMF By component is negative.
Figure 16. Giant flux rope core field directions determined from minimum variance analysis in VSO coordinates, shown in unit scale length.
Figure 17. Giant flux rope core fields spatial distribution in magnetic coordinates in which the upstream IMF points in the Y direction. Z is in the motional electric field direction. The grey circle is Venus.